AMERICAN JOURNAL OF PHYSICAL ANTHROPOLOGY 103:463–469 (1997)

A New, Three-Dimensional Method for Determining Tooth Wear

JOHN T. MAYHALL[1]* AND IKUO KAGEYAMA[2]
[1]*Faculty of Dentistry, University of Toronto, Toronto, Ontario, Canada M5G 1G6*
[2]*Department of Anatomy, The Nippon Dental University School of Dentistry at Niigata, Niigata-city 951, Japan*

KEY WORDS moiré contourography; 3-D; attrition; maxillary molars; tooth wear

ABSTRACT A new technique combining moiré contourography and digital image analysis allows the three-dimensional description of molar wear. It is possible to describe the amount of tooth material lost in a given time, e.g. mm^3/year, and the differing amounts of wear on individual cusps. The moiré technique can be used in conjunction with more conventional quantitative techniques or by itself to assist in age determination in a population. It can be used to describe small amounts of wear that hitherto were difficult to quantify. It is not recommended where the wear includes the greatest convexity of the crown (height of contour) or affects the central fossa. Am J Phys Anthropol 103:463–469, 1997.

There have been many suggestions for measuring the rate, patterns, degree and development of tooth wear. Broca's method (1879) was the first that divided wear into four degrees. Most authors have used a subjective scoring method similar to that of Broca that assigns a score to each degree of wear (Murphy, 1959; Miles, 1963; Molnar, 1971; Smith, 1984). Many of these have depended primarily on the amount of exposed dentin on the occlusal table to derive their methodology. A large amount of data can be obtained easily and quickly by these methods, but quantitative data are not easily gained. Some authors have successfully utilized photographic and planimetric methods to help ameliorate these problems (Walker, 1978; Richards and Brown, 1981; Richards, 1984). These quantitative methods improve on the earlier scoring techniques and contribute a degree of precision that can be applied to the questions of age, habits, and diet. However, the initial stages of tooth wear, presenting unique problems of quantification, have been considered by only a few, e.g. Lambrechts et al. (1989) and Teaford and Tylenda (1991). In many populations, and in younger age groups, the dentin is not exposed but there is evidence of wear on the enamel. It is difficult to accurately decide how much enamel is missing before the dentin below it is exposed. A quantitative approach must be used in these cases to characterize tooth wear, because of its improved accuracy, reliability and reduction in inter-observer error. It is important to have the ability to quantify small changes in wear, especially in slightly worn teeth.

Mehta and Evans (1966) scored the degree of dental attrition by measuring crown height from the cemento-enamel junction to the cusp tip on the occlusal surface to estimate crown loss. Walker and co-workers (1991) devised a method for determining crown height and occlusal wear angles that allowed them to successfully age skeletal material from California. The first study to record cusp height from the lowest point on the occlusal surface was that of Tomenchuk

*Correspondence to: Dr. John T. Mayhall, Faculty of Dentistry, University of Toronto, 124 Edward Street, Toronto, Ontario, Canada M5G 1G6. e-mail: john.mayhall@utoronto.ca

Received 22 November 1996; revised 10 April 1997; accepted 12 May 1997.

and Mayhall (1979). In a cross-sectional study, they measured dental stone casts of Inuit permanent molars using a depth gauge with a dial indicator and recorded the greatest distance from a plane tangent to the surfaces of the mesiobuccal, mesiolingual, and distobuccal cusps (trigon) to the lowest point of the occlusal surface. Molnar and co-workers (1983) more recently have used a similar cusp height determination. They were able to correlate cusp height with age on a longitudinal sample and they noted that the use of a depth gauge although not being able to account for the complex patterns of wear seen on the tooth surface was superior to the earlier qualitative methods. The quantitative methods to date have suffered from the problem that Molnar and his co-workers noted, that only a rather gross measurement of the overall occlusal wear is possible. These methods are unable to account for individual cusp wear patterns and almost always "ignore" the lowest cusp, the hypocone, of maxillary molars. Lambrechts and co-workers (1984) presented an interesting three-dimensional technique for measuring very small amounts of wear of posterior dental restorations that were followed longitudinally. Mayhall and Kanazawa (1989) suggested that the use of moiré contourography as described by Ozaki and Kanazawa (1974) could be applied to determining cusp height and wear of the cusps. A method that combines moiré contourography with digital image analysis to determine not only the reduction in cusp height but also the actual amount of tooth material lost through attrition and abrasion has not been applied to wear studies until the present study. This method adds a dynamic aspect to wear studies by demonstrating the amount of tooth substance lost over a period of time. The method can be used alone or in conjunction with the depth gauge methods as proposed by Tomenchuk and Mayhall, Molnar and co-workers, (or an "improvement" of these noted below) to aid in the age determination of individuals in a population where some can be accurately aged but others cannot.

MATERIALS AND METHODS

To test our procedure, thirteen dental stone models of maxillary first molars from three Australian aboriginals (two females and one male) were photographed using the moiré contourography techniques (Fig. 1) described by Ozaki and Kanazawa (1974). The models from these three individuals were part of a longitudinal study conducted by Brown and Barrett (1973). For each individual either four or five dental stone models were available, covering spans of time averaging 16.58 years (Table 1 and Fig. 2). The youngest age for the inclusion of the first molars was approximately 6 years of age and the oldest was about 26 years. These models represented the condition of the first molar at different ages in the same individual from childhood to early adulthood making it possible to follow the wear of a single tooth over a relatively long period of time. The subsequent images were then transferred to a computer screen where they were digitized. Areal, volumetric and linear determinations were made following the techniques described by Mayhall (1992). The computer screen images which display moiré fringes (contour lines) 0.2 mm apart on the

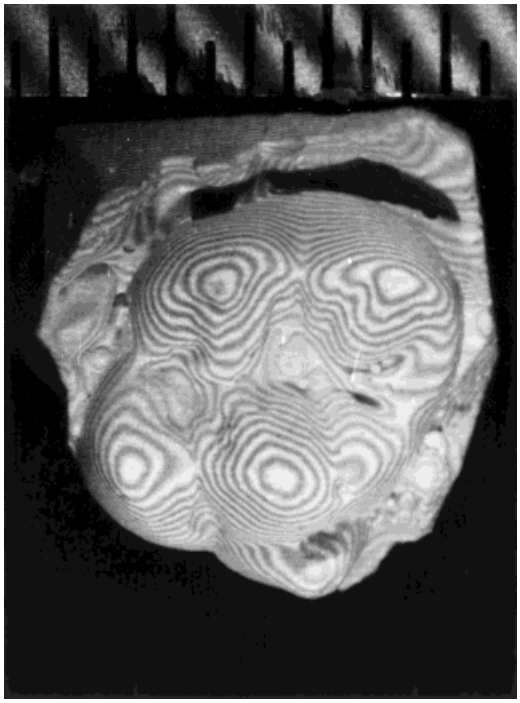

Fig. 1. Moiré fringes projected on a maxillary first molar. The distance between the fringes is 0.2 mm

TABLE 1. Mean cusp height and volume reductions

Sample	No.	Age range (yr)	Initial height (mm)	Final height (mm)	Change/ yr (mm)	Initial volume (mm^3)	Final volume (mm^3)	Difference (mm^3)	Change (mm^3/yr)
Trigon									
Females (F)	2	17.88	2.49	1.87	−0.03897	120.22	93.21	−27.01	−1.5
Male (M)	1	13.99	2.77	1.88	−0.05718	129.46	90.55	−38.91	−2.8
F + M	3	16.58	2.53	1.80	−0.04504	123.30	92.32	−30.98	−1.9
Talon									
Females	2	17.88	2.20	1.50	−0.04143	28.89	22.84	−6.05	−0.3
Male	1	13.99	2.20	1.40	−0.05718	25.02	13.94	−11.08	−0.8
F + M	3	16.58	2.20	1.47	−0.04668	27.09	20.18	−6.91	−0.4
Talon + trigon									
Females	2	17.88	n/a	n/a	n/a	149.11	116.05	−32.06	−1.8
Male	1	13.99	n/a	n/a	n/a	154.48	104.49	−49.99	−3.6
F + M	3	16.58	n/a	n/a	n/a	150.39	112.50	−37.89	−2.3

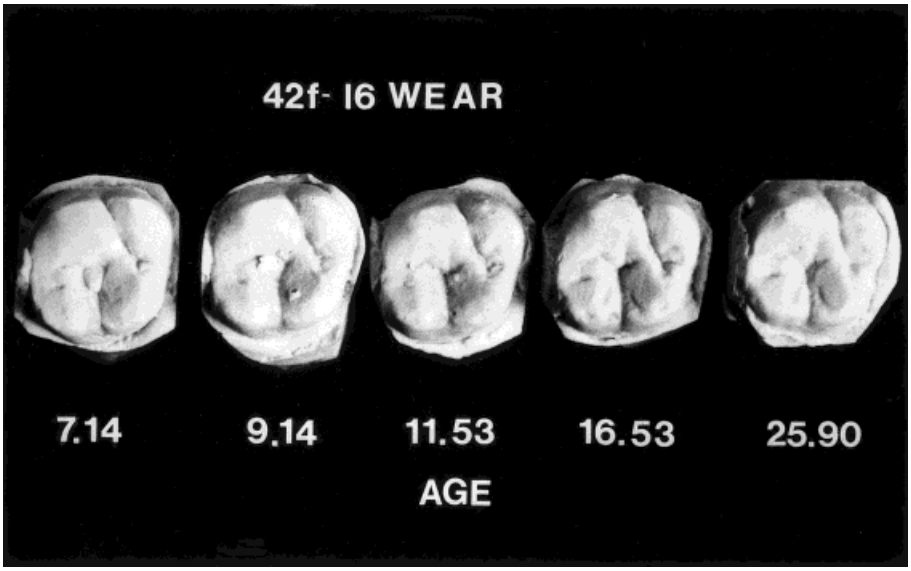

Fig. 2. Example of the progression of wear for one female from age 7.14 years to 25.90 years.

crown were enlarged to between 30 and 60 times their original size to increase the accuracy of on-screen tracing (the accuracy is increased because the image on the screen is larger and one's hand-eye coordination can trace the images easier and with more precision). The use of the fringes allows the determination of cusp height and the ability to determine a "section" through the crown that is parallel to a plane tangent to the cusp tips of the trigon (Mayhall, 1992). All three cusps of the trigon were parallel to the film plane and the plane of the moiré grid. Distances were calibrated using the scale introduced into each image at the time of the original moiré photograph. The tooth was then divided into sections representing the cusps using a mouse to trace the grooves separating them. The lowest point of the occlusal surface (central fossa) was determined and this "depth" used to determine the buccal, lingual, mesial and distal outlines of the crown at that level. (This determination is simple; count the number of fringes from the cusp tip to the lowest point on the occlusal surface and then repeat this procedure on the buccal, lingual, mesial and distal surfaces until the same level is reached.) This results in a "cross-section" through the crown at the same occlusocervical level throughout the crown and does not necessarily represent the widest portion of

TABLE 2. Comparison of methods for determining cusp height (mm)

	No.	Tomenchuk and Mayhall method	Small contact point method	Moiré method
Male				
Deciduous molar	11	1.78	1.87	1.97
First molar	21	2.47	2.59	2.61
Second molar	21	2.31	2.45	2.37
Third molar	14	1.89	1.98	2.01
Female				
Deciduous molar	8	1.71	1.79	1.88
First molar	16	2.31	2.47	2.41
Second molar	16	2.22	2.32	2.38
Third molar	11	1.91	2.07	2.07

the tooth as viewed from the occlusal as has been reported by previous observers (Biggerstaff, 1993; Hanihara et al., 1970). To determine the basal area of a cusp it was outlined at the lowest level on the occlusal surface and the area within this outline determined using digital image analysis. To determine the volume of a cusp this process was repeated by outlining each successive, more occlusal, fringe and determining the area within it. The areas within each of the contour lines were then summed and multiplied by 0.2, the "thickness" in millimeters of each of them. (It should be noted that there may be a slight discrepancy between this determination and the true volume since a "stepped" technique is used. However, the use of trigonometric formulae in an attempt to "smooth" out the curves is virtually impossible due to the varying slopes on different aspects of a cusp and, indeed, on the same surface.) This technique was repeated for each cusp in turn, thus the approximate volume of each cusp is known. The distances between the cusp tips were determined from measurements on the screen and mesiodistal and buccolingual measurements were ascertained by direct measurement of the stone models using dial calipers.

Tooth wear may possibly alter the axis of the crown if the wear is not even on each of the three trigon cusps. This might materially alter any determinations using depth measurement methodologies. However, depth gauge measurements in the past have ignored the orientation of the crown axis with successful results (Molnar et al., 1983; Tomenchuk and Mayhall, 1979). We conducted measurements of the cusp heights using the technique outlined by Tomenchuk and Mayhall and an improved technique utilizing a Mitutoyo depth gauge (no. 547-211) and 0.4 mm diameter ball-point contact point in order to compare the results on the teeth that were utilized in testing the moiré technique. Comparisons were also made of moiré cusp height measurements for the trigon with those made with the depth gauges using a larger sample (37 Australian aborigine males and females with 118 maxillary molars) to determine any differences in the height that might accrue from the varying techniques (Table 2).

RESULTS

Table 1 presents the data for the mean cusp volume reductions of the maxillary first molars. These results are presented here to indicate that the technique outlined above is viable and can be easily applied to individuals and groups where the dynamics of wear are of interest. We have not included the data for individual cusps (except for the hypocone) although these data are readily available with the moiré technique. It is obvious that the small sample sizes give only an indication of the amount of tooth wear that was encountered during this trial of the technique. As can be seen, female cusp volume reduction in both trigon and trigon + talon was smaller than that for the male. Although the difference in the male's cusp volume reduction between the trigon and trigon + talon was 11.08 mm^3, that for the females' was 6.05 mm^3, even though the time interval was shorter for the male. This suggests that the rate of the distolingual cusp volume reduction is larger in the male than in the females and, indeed, that is the case with the male showing over twice the rate of reduction of the females.

Table 2 compares moiré results with those using either the Tomenchuk and Mayhall method or ours using the depth gauge with a smaller contact point. Results using the technique with the depth gauge and the 0.4 mm ball-point contact point were very similar to the present technique but the Tomenchuk and Mayhall technique resulted in a depth determination of up to 0.2 mm shallower. This is apparently because the older technique used a blunter, wider contact point that did not reach the bottom of the central fossa, at least as defined by the moiré technique. Measurements of the larger sample (Table 2) revealed that there was no statistically significant difference in a comparison between the paired measurements of moiré determined cusp height and the small contact point method using the Mitutoyo instrument.

As noted above, one of the possible criticisms of a method to determine the amount of wear using cusp height is the possibility that wear is uneven and, therefore, the plane being used is not consistent. This possibility was examined by noting any changes in the basal area of the tooth. If there were significant reductions in these areas this might indicate that the wear was affecting the outlines of the tooth and, therefore, the orientation of the plane would be significantly changed. The basal areas did not become significantly smaller with age; any reductions were in the range of variation seen in teeth measured multiple times suggesting that if there is any effect from a change in the orientation of the measurements it is minimal at the level of wear examined here and does not materially affect the results. Another reason for utilizing the cusp tips as the plane from which measurements are made is that there appear to be no other stable landmarks on a tooth that are completely unaffected by wear and are observable for all teeth whether they are in the oral cavity or solitary ones outside the oral cavity.

DISCUSSION

The combination of moiré contourography and digital image analysis allows for the determination of the amount of tooth crown lost in a given amount of time where teeth are not excessively worn. It can be used to determine the rate of tooth material lost during various phases of an individual's life allowing for the determination of what period of life might be responsible for most of the lost tooth material. It also has the potential for doing the same for populations where age can be determined.

It is a more objective method of measuring wear than others such as those that have used qualitative methods and can be used as well to improve aging methods. It also entertains the possibility of using a depth gauge to estimate the amount of tooth substance lost by equating the depth measurement using our improved method based on that of Tomenchuk and Mayhall. As an example, a cusp height change of 0.2 mm as measured using the depth gauge might be equated with the results from a moiré measurement that has been reduced by the same amount and an estimate of the amount of tooth material lost will be possible.

Data can be collected by using accurate impressions of teeth rather than having to examine the teeth directly. This can be advantageous where skeletal material must be reburied soon after exhumation. Further, it can be valuable where it is impossible to spend a large amount of time in the field examining worn teeth. Impressions of the teeth can be made using the accurate and low distortion polyvinyl siloxane impression materials (Hembee and Taylor, 1984; Marcinak and Draughn, 1982) and taken to the lab for a more leisurely examination under more ideal conditions. It also has the advantage of allowing studies of tooth wear using dental stone models where it may be impossible to ascertain the amount of dentin exposed. It should be noted that moiré fringes are optimized when the material being photographed is opaque (Takasaki, 1979). Many tissues such as tooth enamel are translucent allowing some of the light to penetrate the enamel and scatter it back to the surface blurring the image. Therefore, opaque, consistent materials such as dental die stones are required.

There are situations where the moiré method may be difficult to use. The time necessary to completely analyze a tooth is approximately 30 min for an experienced

observer. While this may seem excessive the results suggest that it is a worthy investment. The technique is not applicable in situations where there is wear that completely obliterates the cusps. There should be an unworn central fossa and some semblance of cusps for the accurate determination of the cusp height and subsequent determination of cusp volume. The use of moiré contourography requires rather specialized equipment although it is not expensive and can be assembled using materials available at most camera outlets. At present, the technique is only applicable for use on molars, either mandibular or maxillary. To our knowledge only a single moiré study (Mayhall and Townsend, 1995) has characterized any teeth other than permanent first molars. This study examined male Australian aboriginal maxillary deciduous second and permanent first, second and third molars. Because few investigators have as yet used the techniques described above there is a paucity of comparative data. This may not be important, however, depending on the problem that the investigator is examining. Within population data as illustrated in this initial study may be all that is required. Cross-sectional studies are also possible once unworn teeth are used to establish cusp heights, basal areas and volumes.

The combination of moiré contourography and digital image analysis holds promise for increasing our ability to accurately estimate the amount of tooth wear over time. It allows for the determination of wear in situations such as slightly worn teeth that up to now were difficult to measure accurately and consistently. This will allow for more accurate age determinations as well as providing a dynamic characterization of not only general occlusal wear but also the wear of individual cusps.

ACKNOWLEDGMENTS

We thank Professor Grant Townsend for permission to examine the materials used for testing our technique. Dr. Kageyama's participation was made possible by a study leave grant from the Nippon Dental University at Niigata. The equipment used in the study was purchased with a grant from the J.P. Bickell Foundation of Canada.

LITERATURE CITED

Biggerstaff RH (1973) Heritability of the Carabelli cusp in twins. J. Dent. Res. *52:*40–44.

Broca P (1879) Instructions relative á l'étude anthropologique du systéme dentaire. Bull. Soc. Anthropol. *2:*128–152. (As cited by Walker *et al.*, 1991)

Brown T, and Barrett MJ (1973) Dental and craniofacial studies of Australian aborigines. In RL Kirk (ed.): The Human Biology of Aborigines in Cape York. Canberra: Australian Institute of Aboriginal Studies, pp. 69–80.

Hanihara K, Tamada M, and Tanaka T (1970) Quantitative analysis of the hypocone in the human upper molars. J. Anthropol. Soc. Nippon *78:*200–207.

Hembee JH, Jr., and Taylor TJ (1984) Comparative accuracy of some new impression materials used for indirect techniques. Tenn. Dent. J. *64:*33–35.

Lambrechts P, Vanherle G, Vuysteke M, and Davidson CL (1984) Quantative evaluation of the wear resistance of posterior dental restorations: A new three-dimensional measuring technique. J. Dent. *12:*252–267.

Lambrechts P, Braem M, Vuylsteke-Wauters M, and Vanharle G (1989) Quantitative in vivo wear of human enamel. J. Dent. Res. *68:*1752–1754.

Marcinak CF, and Draughn PA (1982) Linear dimensional changes in addition curing silicone impression materials. J. Prosthet. Dent. *47:*411–413.

Mayhall JT (1992) Techniques for the study of dental morphology. In SR Saunders and MA Katzenberg (eds.): Skeletal Biology of Past Peoples: Research Methods. New York: Wiley-Liss, pp. 59–78.

Mayhall JT, and Kanazawa E (1989) Three-dimensional analysis of the maxillary first molar crowns of Canadian Inuit. Am. J. Phys. Anthropol. *78:*73–78.

Mayhall JT, and Townsend G (1995) The relationships of the three-dimensional morphology of permanent and deciduous molars: an initial report. In RJ Radlanski and H Renz (eds.): Proceedings of the 10th International Symposium on Dental Morphology. Berlin: M Marketing Services, pp. 151–155.

Mehta JD, and Evans CC (1966) A study of attrition of teeth in the Arkansas Indian skulls. Angle Orthod. *36:*248–257.

Miles AEW (1963) Dentition in the assessment of individual age in skeletal material. In DR Brothwell (ed.): Dental Anthropology. London: Pergamon, pp. 191–209.

Molnar S (1971) Human tooth wear, tooth function and cultural variability. Am. J. Phys. Anthropol. *34:*175–190.

Molnar S, McKee JB, Molnar IM, and Przybeck TR (1983) Tooth wear rates among contemporary Australian aborigines. J. Dent. Res. *62:*562–565.

Murphy T (1959) The changing pattern of dentine exposure in human tooth attrition. Am. J. Phys. Anthropol. *17:*167–178.

Ozaki T, and Kanazawa E (1984) An application of the moiré method to three-dimensional measurements of the occlusal aspects of molars. Acta Morphol. Neerl. Scand. *22:*85–91.

Richards LC (1984) Principal axis analysis of dental attrition data from two Australian aboriginal populations. Am. J. Phys. Anthropol. *65:*5–13.

Richards LC, and Brown T (1981) Dental attrition and age relationships in Australian aboriginals. Archaeol. Oceania *16:*94–98.

Smith BH (1984) Patterns of molar wear in hunter-gathers and agriculturalists. Am. J. Phys. Anthropol. *63:*39–56.

Takasaki H (1979) The development and the present status of moiré topography. Optica Acta *26:*1009–1019.

Teaford MF, and Tylenda CA (1991) A new approach to the study of tooth wear. J. Dent. Res. *70:*204–207.

Tomenchuk J, and Mayhall JT (1979) A correlation of tooth wear and age among modern Igloolik Eskimos, Am. J. Phys. Anthropol. *51:*67–77.

Walker PL (1978) A quantitative analysis of dental attrition rates in the Santa Barbara Channel area. Am. J. Phys. Anthropol. *48:*101–106.

Walker PL, Dean G, and Shapiro P (1991) Estimating age from tooth wear in archaeological populations. In MA Kelley and CS Larsen (eds.): Advances in Dental Anthropology. New York: Wiley-Liss, pp 169–178.